3Dπ: Utilizing Noble Liquid Detection to Improve Positron Emission Tomography

Link to recording

https://drive.google.com/file/d/1WTyIEJzoXuuG-rcW00OXE-IpEG-8lX5O/view?usp=sharing

Outline

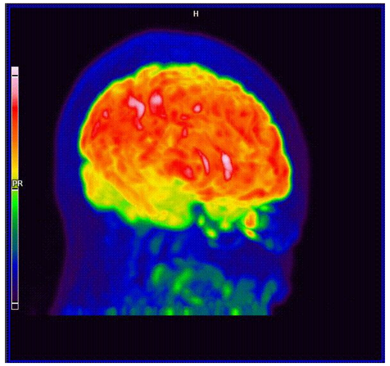
1. Background and Context
2. Project Introduction
3. White Paper Status
4. Current Results
5. Ongoing work
6. Hardware

1 – Background and Context

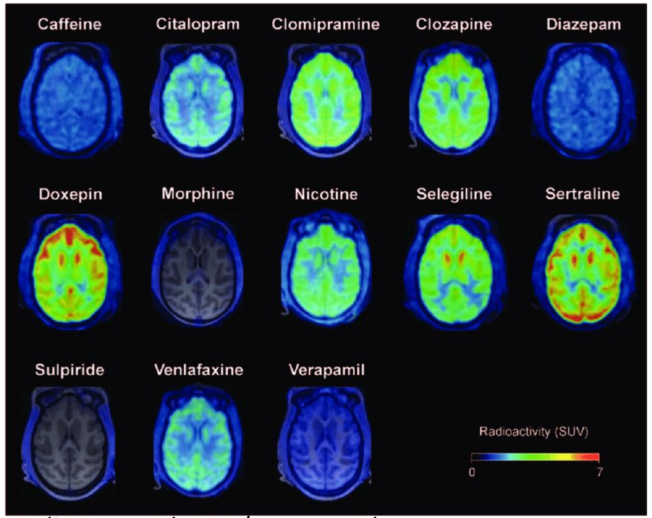
1 - Background on PET

- Positron Emission Tomography (PET) is a medical imaging technique used to observe metabolic activity in cells and tissue
- Used to locate tumors and diagnose patients.
- Monitor patient’s response to therapy
- Developed in the mid to late 20th century

Credit: Bonsecours/Positron Emission Tomography



Credit: http://www.nucradshare.com/Neuro.html



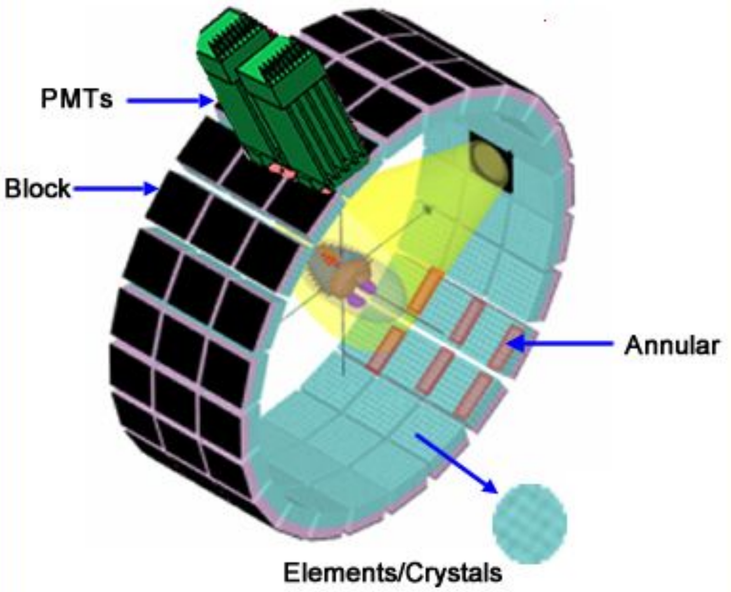
Credit: ResearchGate/Magnus Schou

1 – Traditional Method of Detection

- Current scanners use a crystal scintillator with a photosensor
  - Photomultiplier tube (PMT)
  - LYSO crystal
  - Push for Silicon Photomultipliers (SiPMs) to replace PMTs
  - Single sided
  - Usually, one layer of crystals and sensors in a ring

Material	Peak Emission(nm)	Light Yield (ph/MeV)	Energy Res. @ 661.7 keV	Decay Time (ns)
BGO	480	8000-10000	9.7-16%	300
LYSO	420	30000-33000	8-20%	45

Credit: 10.3390/s19183828

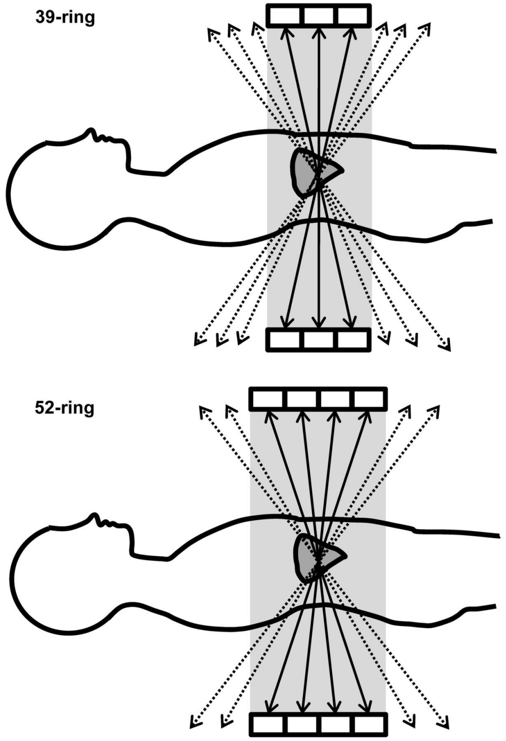


Another angle of the PET Components

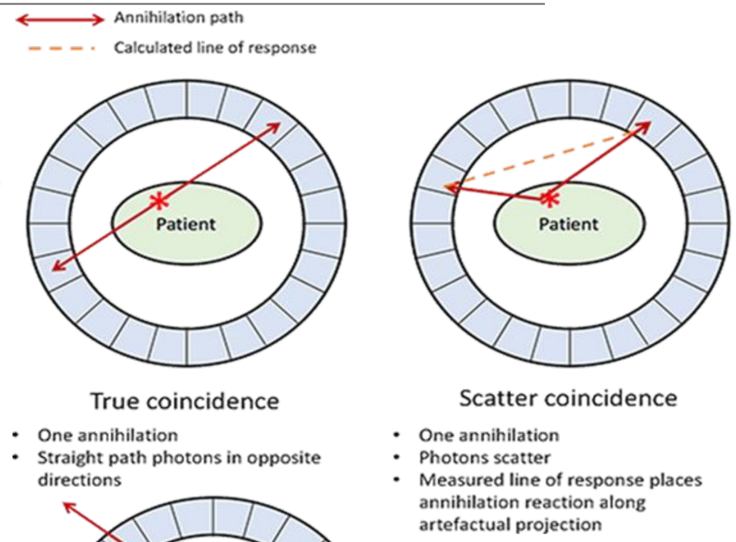
Credit: http://www.people.vcu.edu/~mhcrosthwait/PETW/petinstrumentation.html

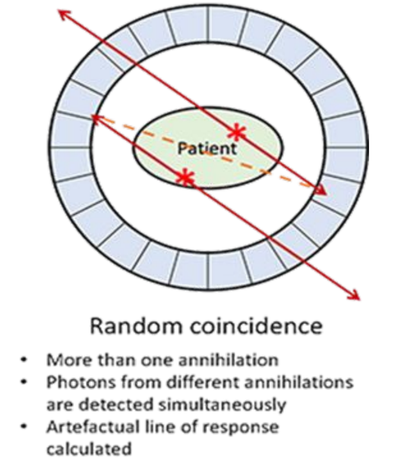
1 - Research Motivations (PET Limitations)

- Scanners can only survey sections of patients. (~20-30 cm)
- Small sensitivity for gamma detection.
- Unable to image and observe activity of multiple body parts simultaneously
- Increasing dosage raises sensitivity but produces more gamma scattering. Leads to false coincidences



Credit: http://tech.snmjournals.org/content/42/2/101/F1.expansion.html





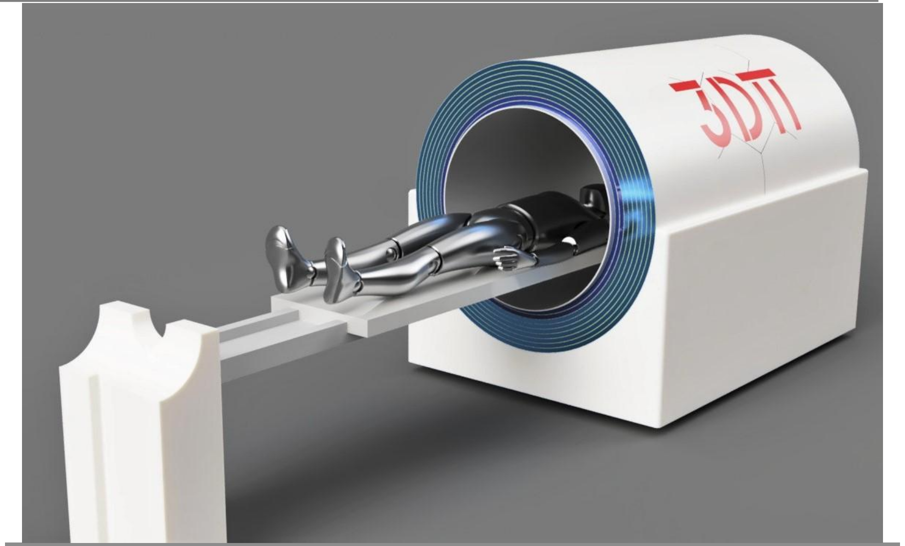
Credit: https://www.radiologycafe.com/radiology-trainees/frcr-physics-notes/pet-imaging

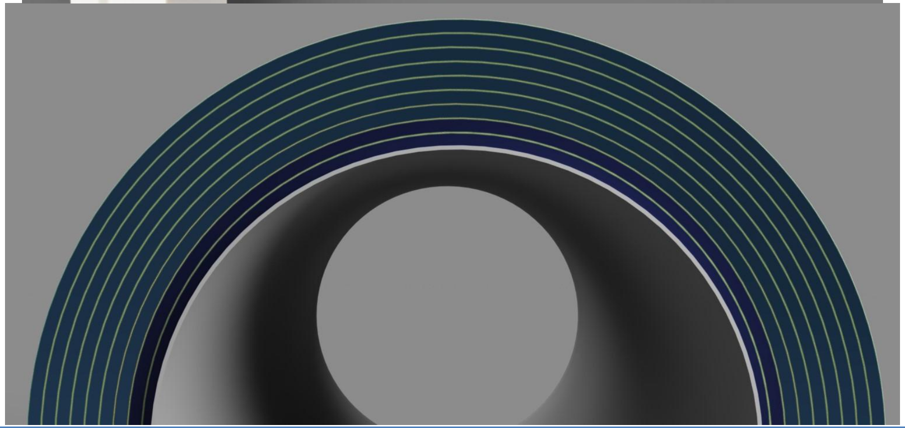
2 – Project Introduction

2 - 3-Dimensional Positron Identification (3DPi)

- A full body, Time of Flight PET scanner
  - Using SiPMs instead of PMTs
  - Liquid Argon scintillation
    - Multiple layers

- Geometry:
  - 9 annulus detection rings
  - Each ring has Liquid Argon sandwiched between two layers of SiPMs
  - PTFE supporting structure
  - 2 m in length



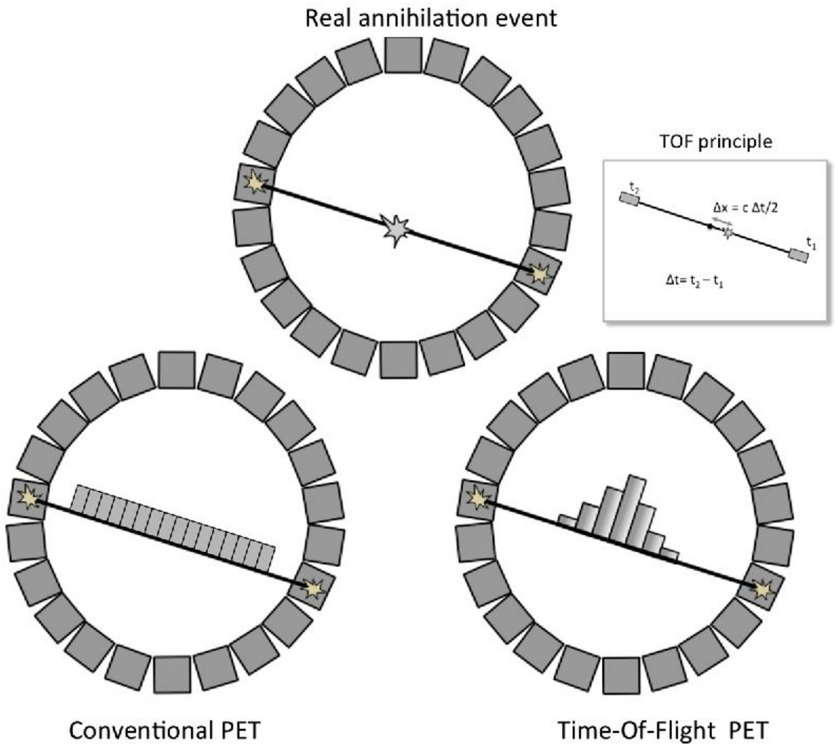


2 - Time of Flight (TOF)

- Using TOF info of annihilation photons to improve image quality
- Use SiPMs
- Improves signal to noise ratio (SNR)

$$\Delta x = c\frac{\Delta t}{2} \qquad \Delta t = t_2 - t_1$$

Delta x is the distance from the center of the rings to annihilation vertex



Credit: https://www.semanticscholar.org/paper/Recent-developments-in-time-of-flight-PET.-Vandenberghe-Mikhaylova/47b546d92f8633d3602553d8e0335092964e351e

2 – Full Body

- A scanner that covers entire patient significantly increases sensitivity
- Easier 3-D annihilation vertex reconstruction and imaging.
- Image entire body at once and observe responses from multiple body parts
- Scanner configuration allows for custom tradeoffs

Explorer Scanner (UC Davis Health)

$$SNR \propto \sqrt{\underbrace{S}_{\text{Sensitivity}} \cdot \overbrace{A}^{\text{Activity}} \cdot \underbrace{T}_{\text{Scan time}}}$$

2 – Xenon Doped LAr

- The Triplet light component of LAr is too slow
- Alternative is xenon doped liquid argon (LAr + Xe)
  - Possible concentrations up to 1000 ppm
  - Suppresses long decay component from 1 µs to ~90 ns around 100 ppm and beyond
  - Increase in light yield from xenon doping

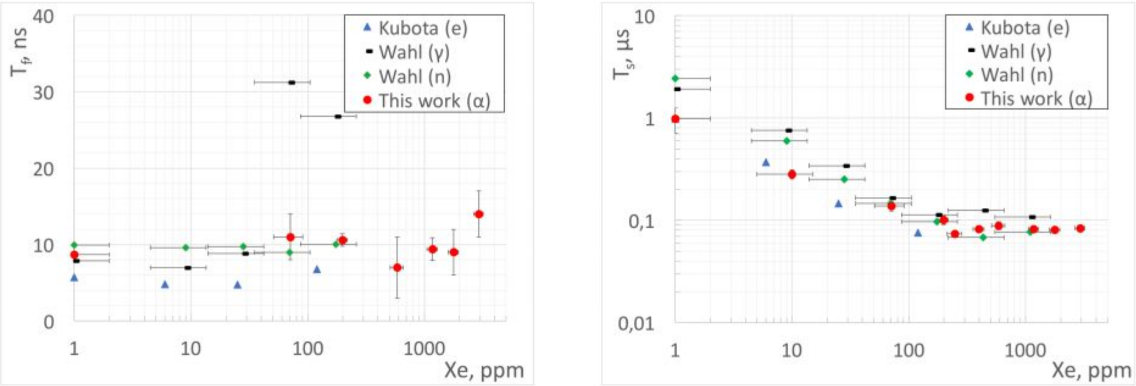


Figure 7. Fast (left) and slow (right) decay times for different Xe concentrations.

Credit: arXiv:1906.00836

Property	Argon	Xenon
Fast decay time (ns)	7	4.3
Slow decay time (ns)	1600	22
Light yield (photons/keV)	40	42
Wavelength (nm)	128	175
Density at boiling temperature at 1 atm (g/cm^3)	1.40	2.94
Cost (US$/kg)	~2	~2000

Credit: arXiv:1403.0525

3 – White Paper Status

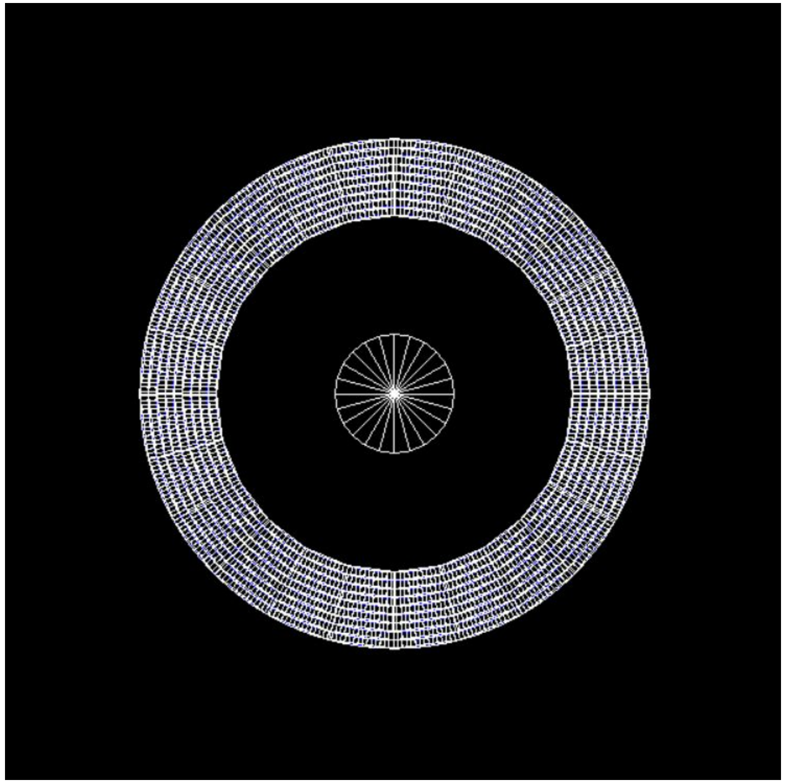
3 – White Paper Status

- Updating references
- Include EXPLORER scanner and others to show comparisons
- Tailor paper to medical physics journal instead of physics one
  - Formatting
  - Structuring sections
- Updated NEMA guide reference (NU-2018)
  - Updated phantom geometries
- Updating plots
- Aim for End of July - Early August for draft

4 – Current Results

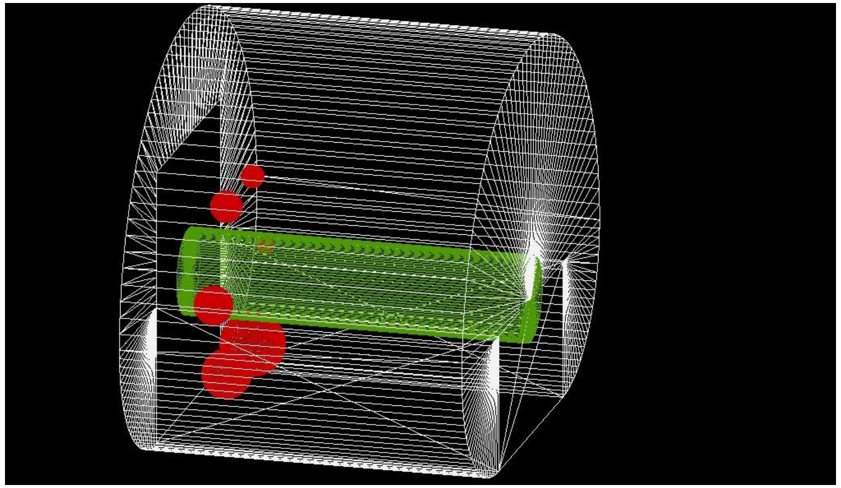
4 - Geant4 Simulations

- Simulations based off the Geant4 from DarkSide
  - Optical properties of LAr Scintillation light
  - Real DarkSide-50 detector data used
- 9 double sided layers of SiPM panels
  - SiPMs assumed a 60 ps intrinsic timing resolution
  - Each SiPM layer has ~20 mm LAr thickness
  - Titanium cryostat assumes a thickness of 6mm
  - Simulation TOF resolution of ~100 ps
  - Most current TOF-PET systems have resolutions of ~500-600 ps



4 - NEMA Tests

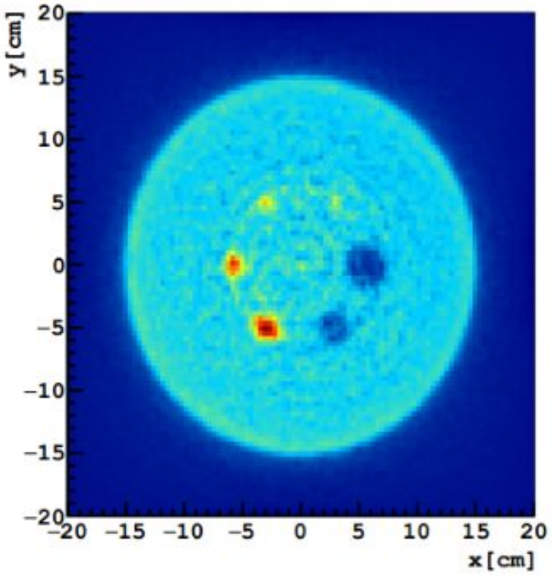
- The National Electrical Manufacturers Association (NEMA) has a guide to characterize PET performance
- Use these tests to compare with other scanners
- Used the guide NEMA NU 2-2012
- Conducted the tests
  - Spatial Resolution
  - Image Quality
  - Sensitivity
  - Scatter Fraction



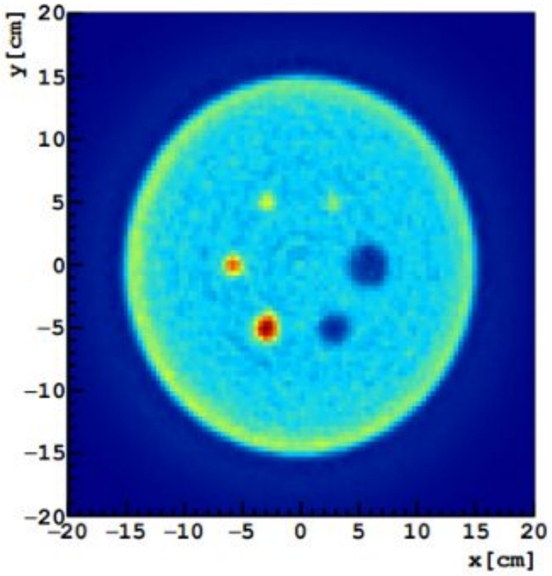
4 - Image Quality

- 4 radioactive sources with 2 water sources arranged in a ring
- Each source varies in size and activity

LAr + TPB

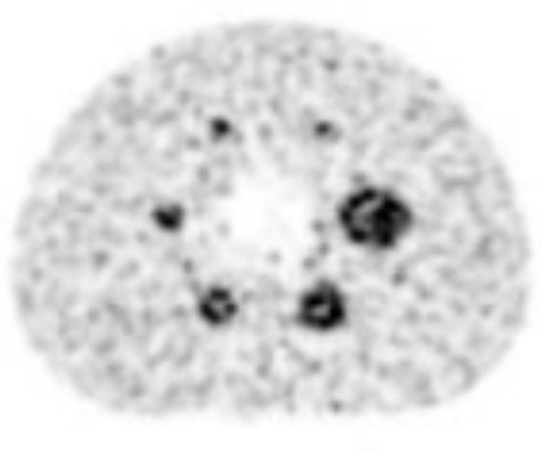


LAr + Xe



10^9 Annihilations
15 - 30 second scan

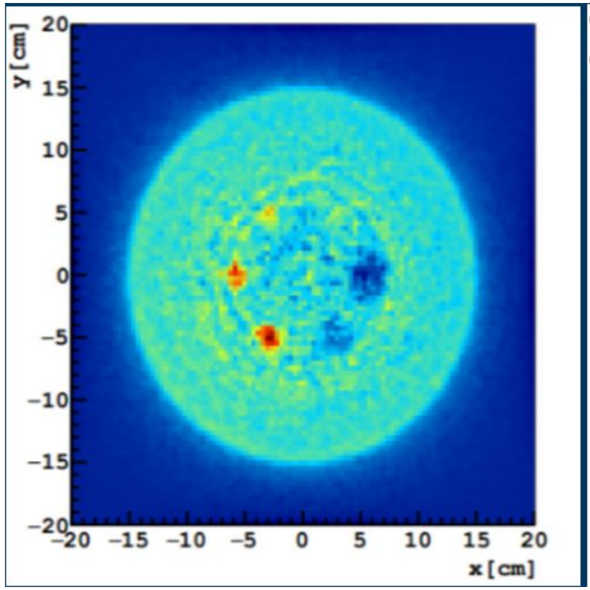
Crystal Scintillator (EXPLORER)



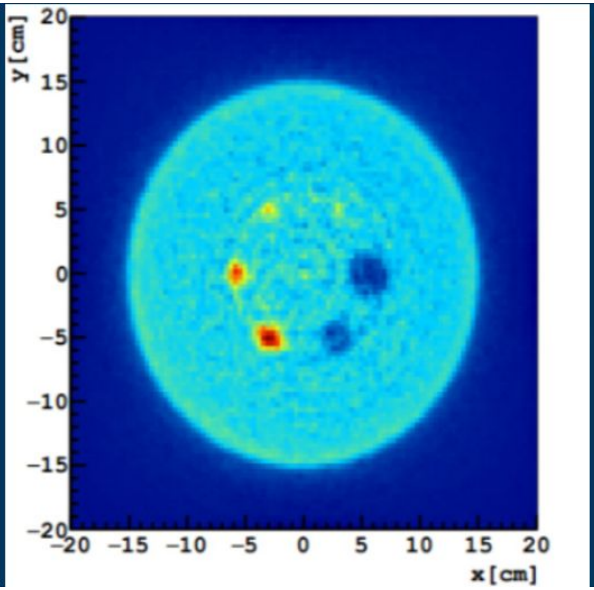
~1.06 x 10^9 Annihilations
10 min scan

4 - Image Quality

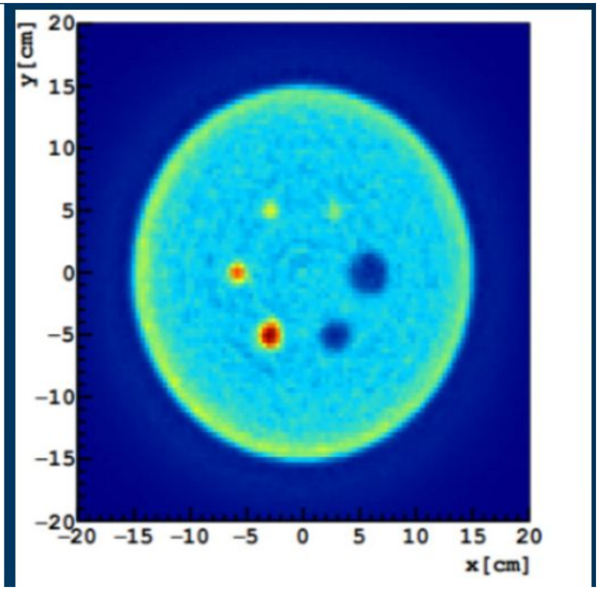
LAr + TPB W/o filtering



LAr + TPB

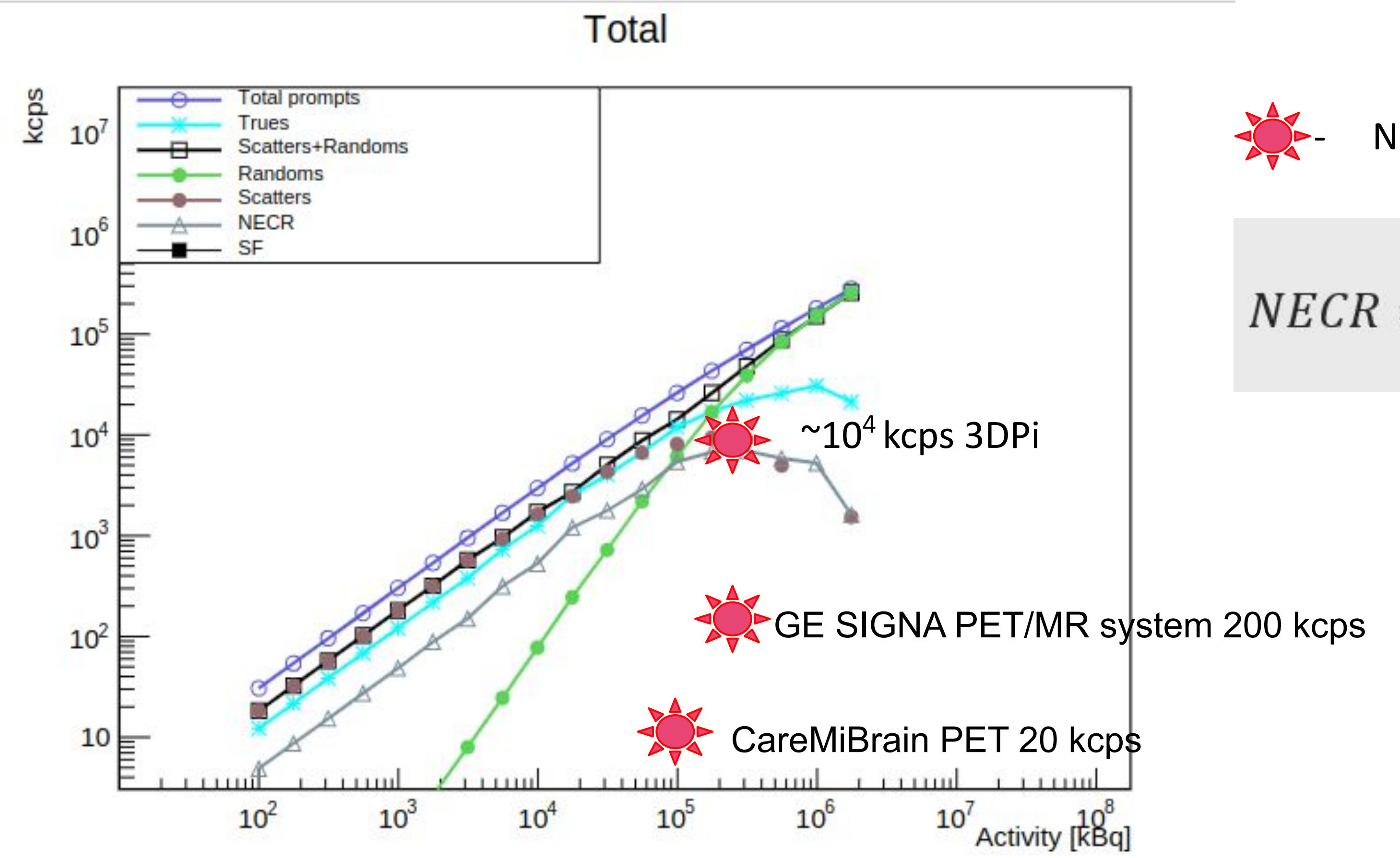


LAr + Xe



10^9 Annihilations
15 - 30 second scan

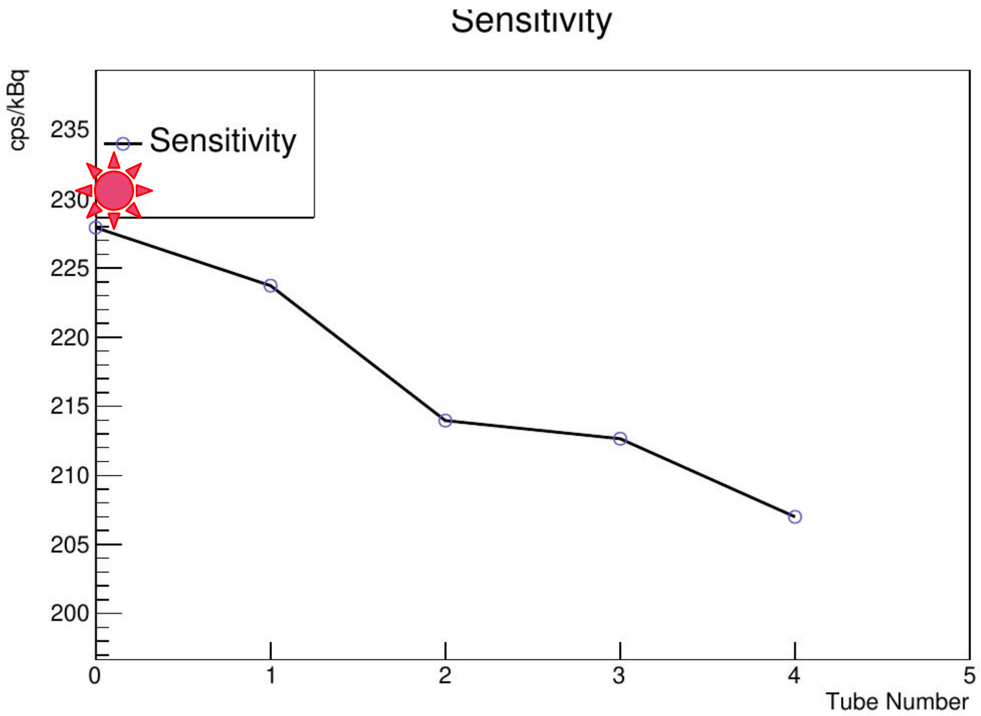
4 - Scatter fraction, count losses, and randoms



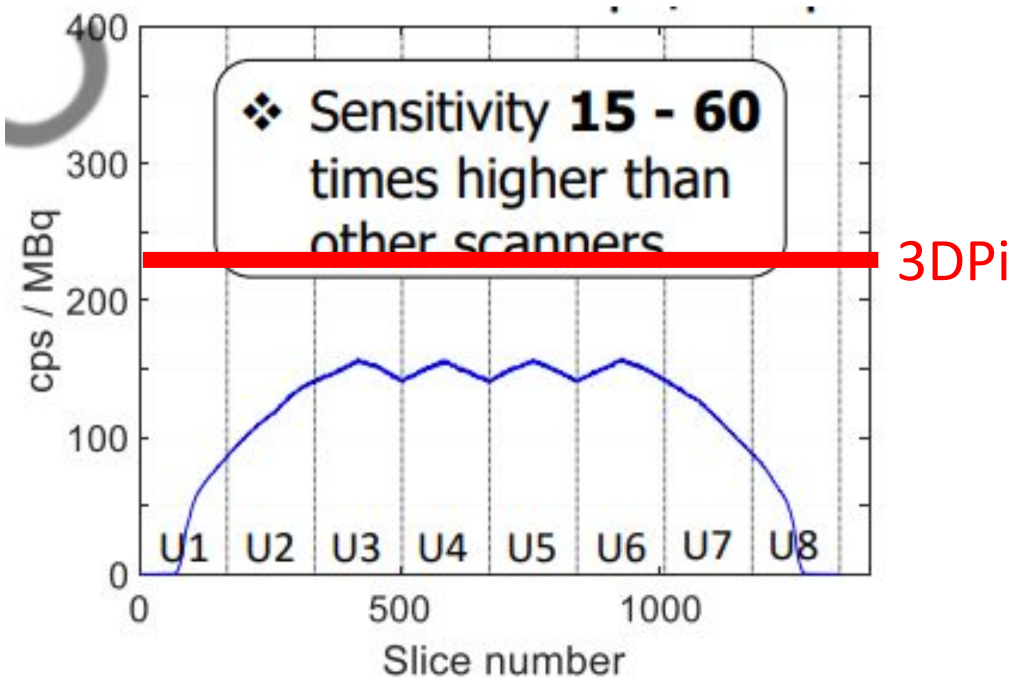
- NECR Maximum

$$NECR = \frac{T^2}{S+T+R}$$

4 - Sensitivity at center

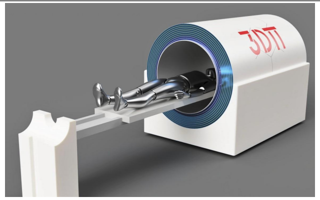


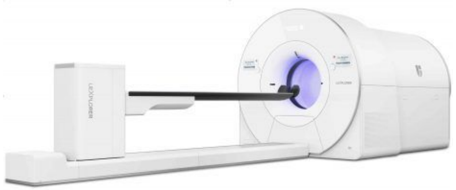
Our Total-Body TOF-PET:
230 kcps/MBq



EXPLORER Total-Body PET/CT
Scanner: 147 kcps/MBq

4 - Spatial and Sensitivity Comparison





	Values	LAr + TPB	LAr + Xe	GE Signa PET/MR	GE Discovery 710 PET/CT	Explorer (Full body TOF-PET)
Center Position (1 cm)	σ_tangential (mm)	7.4	4.4	4.7	4.7	2.9
	σ_radial (mm)	4.6	4.4	4.4	4.9	3.2
Off-center Position (20 cm)	σ_radial (mm)	5.3	4.4	8.4	5.3	4.8
	σ_tangential (mm)	17.5	5.7	5.2	4.8	4.6
	σ_axial (mm)	-	-	7.3	5.6	3.4
	Sensitivity (kcps/MBq)	-	230	23.3	5.5	~147
	Timing Res. (ps)	~100		~ 400	-	~490

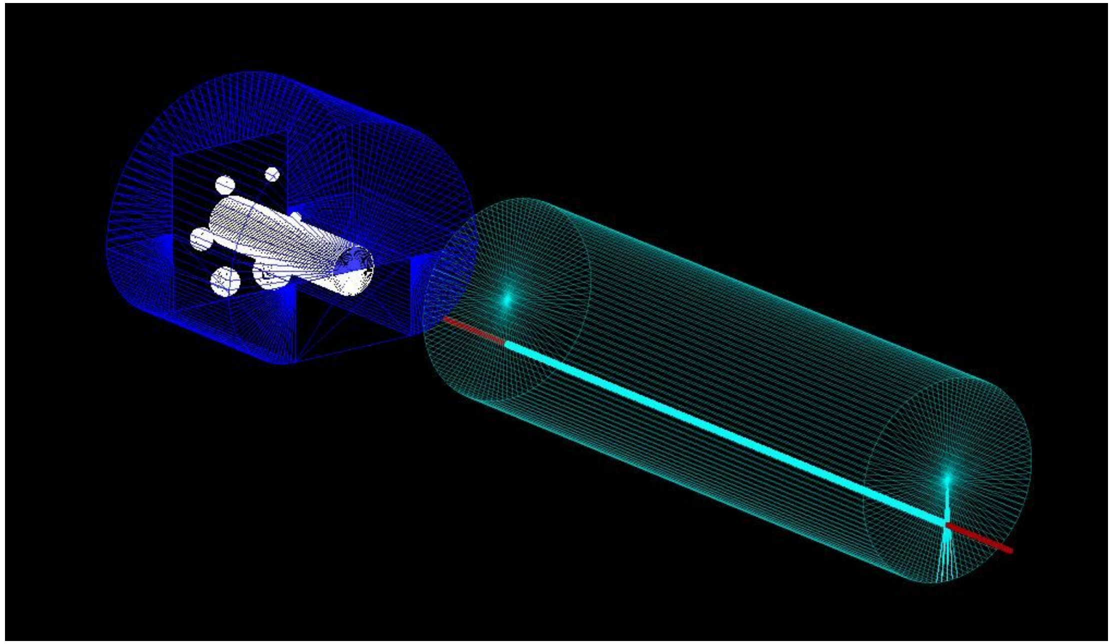
5 – Ongoing Work

5 – Next Steps

- FBP does not account for noise
  - Use an iterative reconstruction algorithm
- Optimize processing code, more streamlined
- Simulation needs to be more realistic
  - Incorporate realistic geometry, human phantom
- Geometry needs to be optimized
  - Remove layers to simplify geometry, adjust LAr thickness?
- Can ML be implemented to produce better images?
- Add in electronics layers

5 – Simulations

- Geant4 code has been updated include F18 energy spectrum
- Cherenkov light implemented
- Updated NEMA phantom geometries from updated NEMA guide 2018
  - New Image quality phantom from NEMA 2018
  - New sensitivity phantom offset
- Resubmit simulations to reflect changes



6 – Hardware

3D∏

Necessary R&D

Fast time resolution
with SiPM + readout electronics

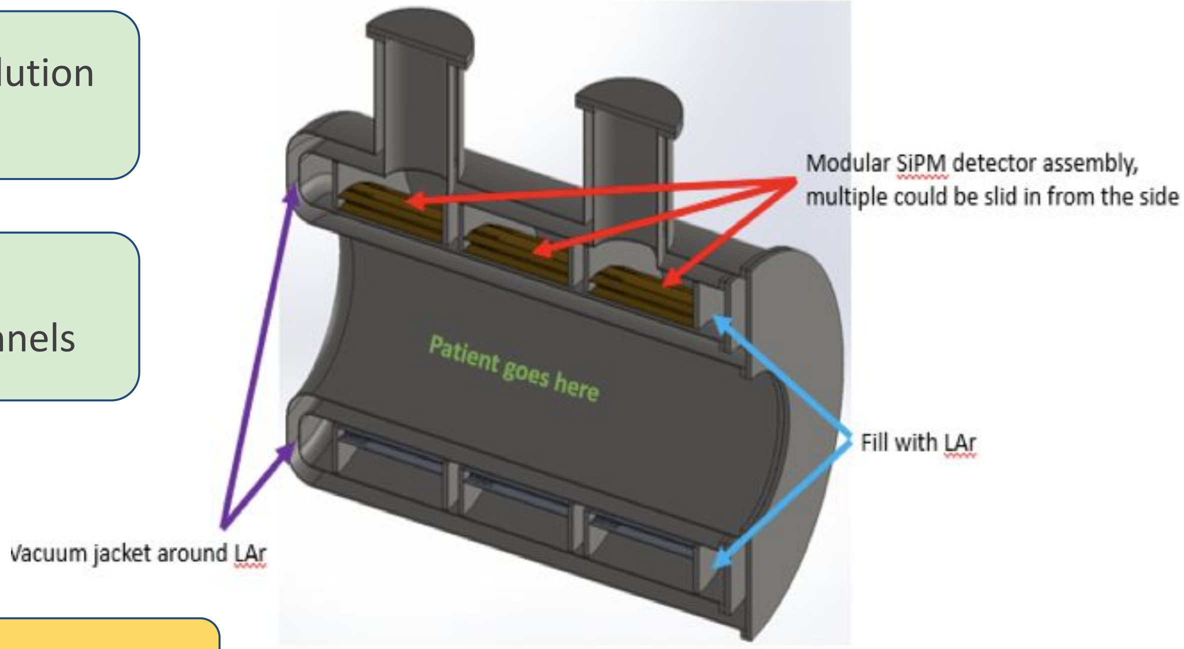
measure time resolution
with SiPM + ASIC

Develop DAQ to
readout many channels

Stability of Xe-doped LAr

Optimization of cryostat design

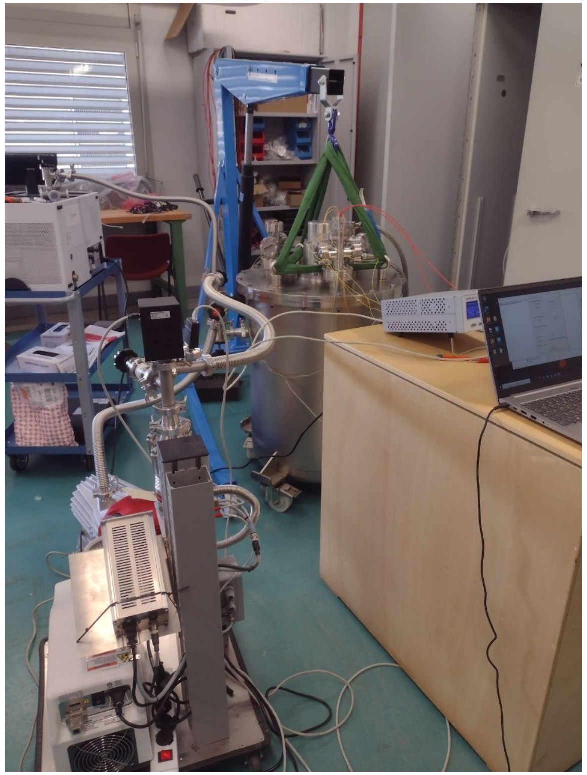
Optimization of condenser and
circulation system



6 – Ongoing activities

- Setup at INFN Cagliari, to test **Coincidence Time Resolution** in the liquid argon-xenon mixture
- Setup at Princeton to test stability of the Xe-doped LAr

- Agreement with Fondazione Bruno Kessler to test custom developed SiPM, tile size 3x3 mm^2
- Scaling up to 10x10 mm^2 would reduce the amount of channels
- Testing of the ALCOR chip at cryogenic temperature

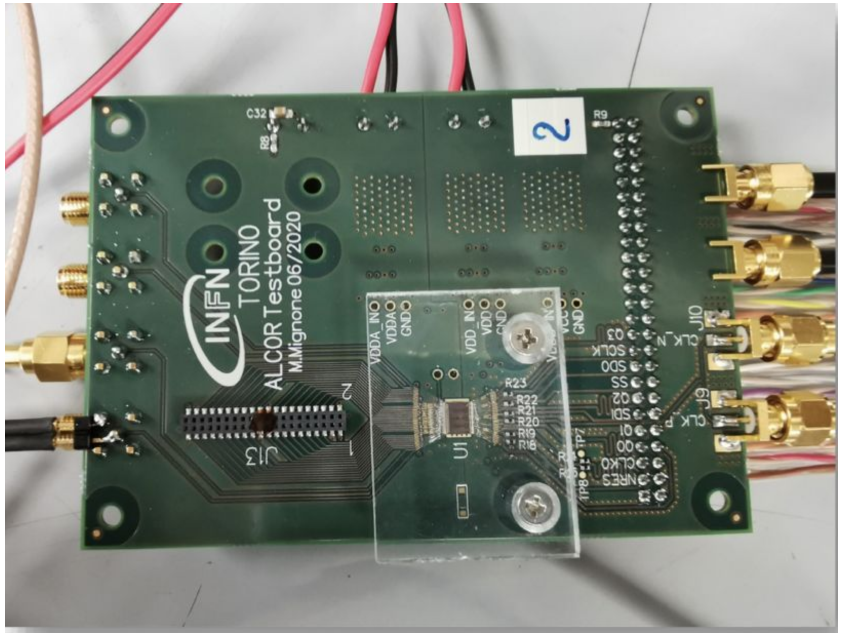


6 – Next step

- Need to develop the electronics for the scanner

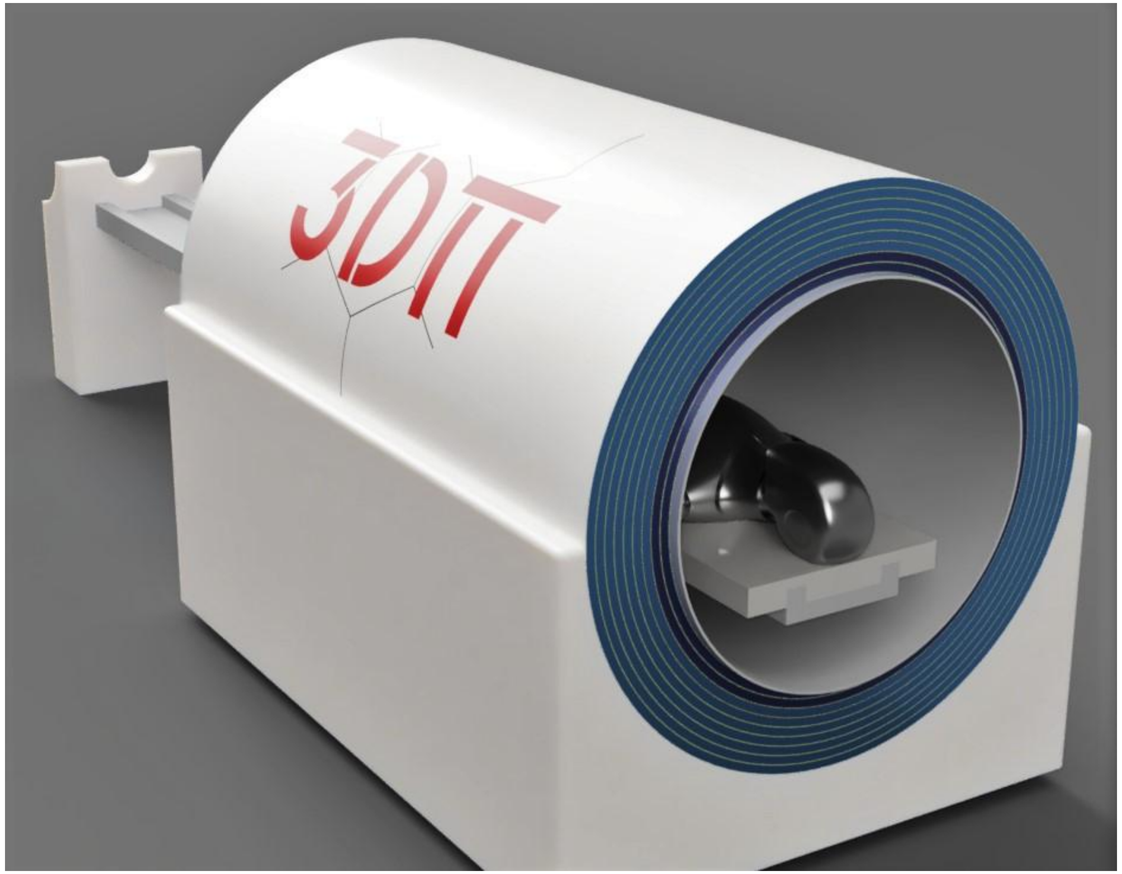
- Front-end electronics requirements:

  → 1 milion channels to read
  → Optimized for timing measurements
  → Low power consumption (5 mW/channel)
  → High event rate (50 MHz)



Advantages of 3DPi (Summary)

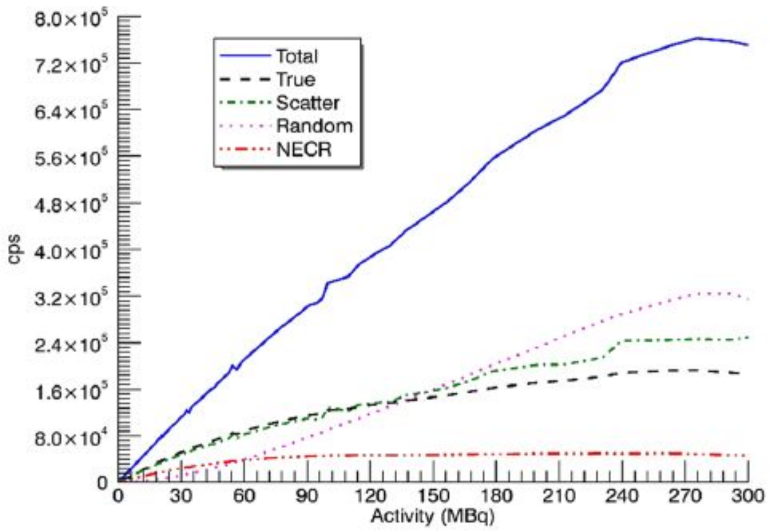
- Large scanner yields higher sensitivity
- LAr + Xe + SiPMs allows for fast scintillation
  - Better Timing Resolution
  - Better Spatial Resolution
- LAr cryogenics reduces SiPM Dark counts
- Monolithic scintillator
- LAr lower optical density than crystal scintillators



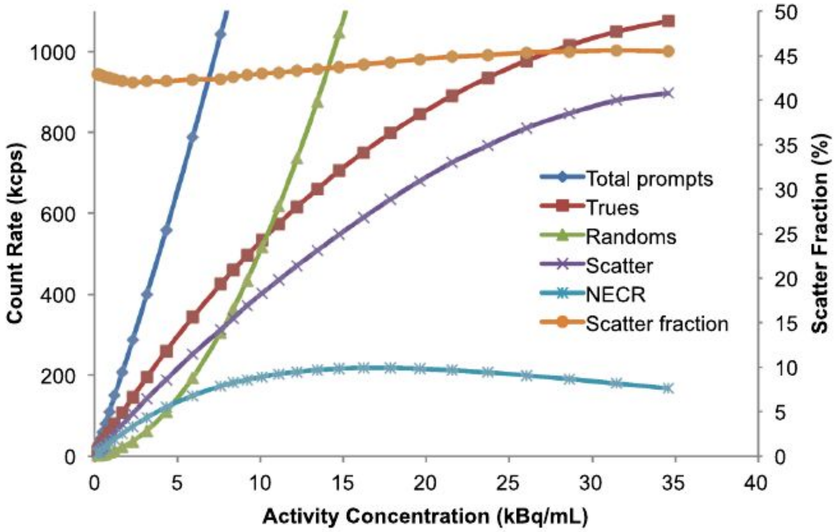
Thank You

Backup

Other scanners SF



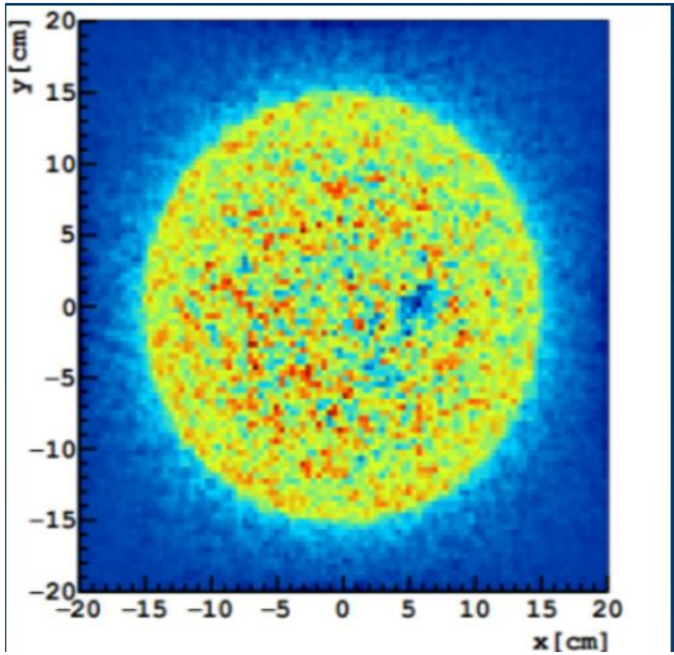
CareMiBrain PET



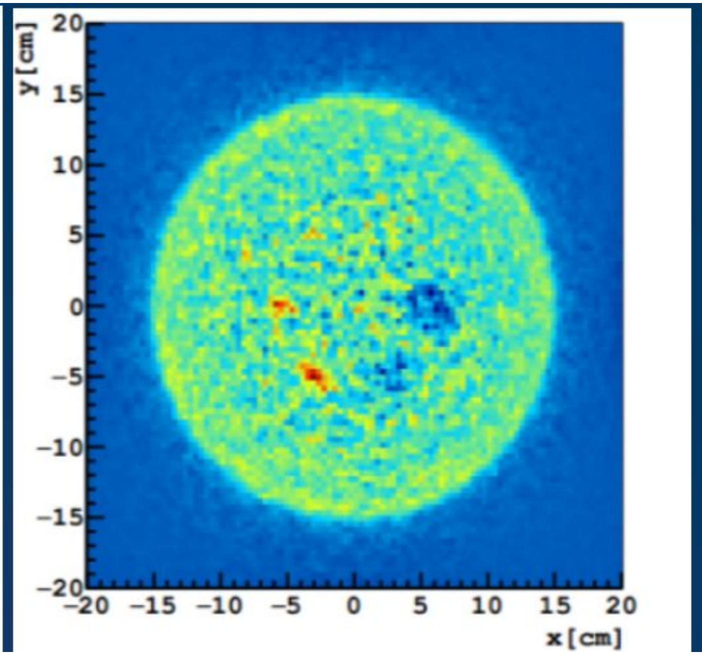
GE SIGNA PET/MR system

4 - Image Quality

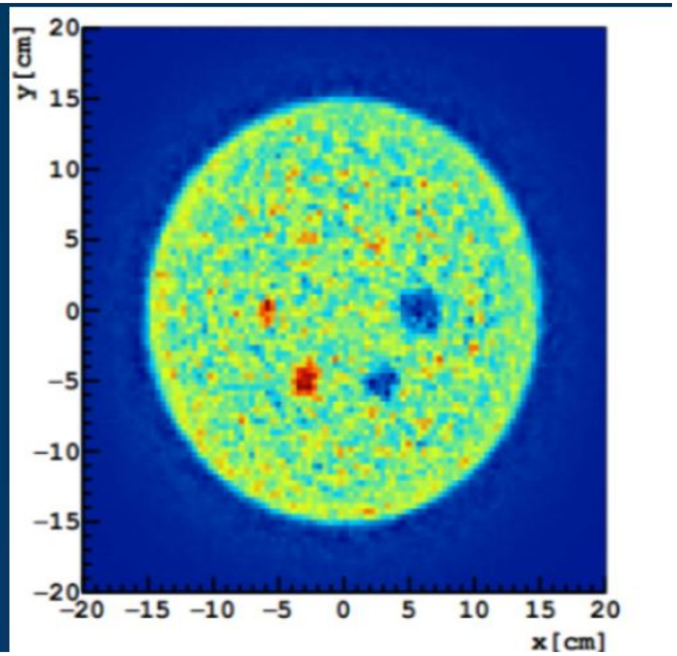
LAr + TPB W/o filtering



LAr + TPB



LAr + Xe



10^8 Positron Annihilations. < 15 second scans